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Climate Change Impacts on Irrigation Requirements of Preserved Forage for Horses under Mediterranean Conditions

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Abstract: Pasture and forage production occupies a large part of the utilized agricultural area in Portugal, a country prone to the effects of climate change. This study aims at evaluating the impacts of climate change on forage irrigation requirements and at defining and assessing different adaptation measures. A second objective focuses on evaluating the impacts on water deficit of rainfed forages. This study was performed in a *Lusitano* horse stud farm located in Azambuja Municipality, Portugal. The climate change impacts on the crop irrigation requirements and crop water deficit were simulated using the soil water balance model, ISAREG. The reference period considered was 1971–2000 and the climate scenarios were the Representative Concentration Pathways (RCPs) 4.5 and 8.5 (2071–2100). The results show that the adaptation measure aiming at maximum production (several cuts) will increase the irrigation requirements in the different climate change scenarios between 38.4% and 67.1%. The adaptation measure aiming at reducing the water consumption (only one cut) will lead to a reduction in irrigation requirements in the different climate change scenarios, ranging between −31.1% and −64.0%. In rainfed conditions, the water deficit is substantially aggravated in the climate change scenarios.

Keywords: climate change scenarios; adaptation measures; hay; haylage; irrigated crops; soil water balance model; crop water requirements; water deficit; growing degree-days

1. Introduction

A large part of Portugal is under Mediterranean conditions, characterized by rainy winters and hot dry summers. Projected climate changes (CCs) for Portugal point to air temperature increase, precipitation decrease, especially during spring, and a higher risk for the occurrence of extreme events such as droughts [1–6]. These changes will have strong impacts on agricultural production and water resource management with water considered as the most important, yet vulnerable, resource in the Mediterranean region [7]. A study developed by Rolim et al. [8] shows that for the spring–summer crops produced in Portugal, an increase in water requirements is projected, associated with a reduction in crop productivity. This study also highlights the high vulnerability of rainfed crops in southern Portugal, for the future climate change scenarios (CCSs), considering the expected increase in water scarcity [4,5]. Therefore, negative impacts in pasture and forage production are expected, namely a reduction in forage productivity due to an increased water deficit [9], accentuating interannual climate variability, which will lead to more variable pasture production [10], emphasizing the need to use preserved forages. Furthermore, preserved forages are fundamental as a feed resource in equine production systems, especially in Mediterranean environments, where grazing is not possible during some parts of the year or during periods of drought. The horse is a grazing herbivore adapted to eating plant-fiber or forage-based diets and therefore their diets should contain a minimum daily amount of forages [11]. Thus, the negative effects of climate change on forage production may have important impacts on stud farms.

Forage production relies directly on weather conditions, being particularly vulnerable to periods of drought, with considerable impacts on production—i.e., on the length of the growing period [12,13], productivity and quality of forage and pasture [6,14] and their irrigation requirements [9]. In Portugal, the production of pasture and forage occupies 11.3% (129029 ha in 2018; [15]) of the Utilized agricultural area, with the majority of these crops being produced under rainfed conditions, where precipitation is the only available source of water for plant growth [16]. The reduction in precipitation and the increase in reference evapotranspiration (ETo), projected for the future CCS, will aggravate the already difficult conditions of rainfed production in the Mediterranean area, raising the pressure to increase the irrigated area and its productivity [17]. Similar conclusions were obtained by Pessacg et al. [18] for other climatic conditions (northern Patagonia) where rainfed forages are expected to suffer sharp production losses, associated with a high water deficit caused by reduced precipitation and increased evapotranspiration. Given this dependence on the weather conditions and the climate changes that have been already observed in Portugal [5,19], it is relevant to study climate change impacts on forage production. Moreover, the horse breeding sector in Portugal has an important revenue and it is imperative to provide secure operative feeding systems.

To evaluate the CC impacts on agriculture, crop simulation models or soil water balance models are usually adopted, using the climate scenarios produced by climate models as input data. The soil water balance models allow to estimate the impacts on crop water consumption, simulating different climate scenarios and agronomic scenarios, including adaptation measures. As an example of climate change impacts studies based on the use of soil water balance models, the work developed by Popova [20], Valverde et al. [3,21], Rolim et al. [8], Yang et al. [13], Tanasijevic et al. [22] and Saadi et al. [23] can be referred to. In the scope of soil water balance models, the ISAREG model [24] has already been applied to a large number of crops and climate conditions, including winter cereals [25] and grassland [26]. These studies concerning the impacts of climate change on crop irrigation requirements are subject to uncertainties resulting from the use of simulation models, but also due to the uncertainty of plant responses to climate change. Increased CO_2 levels may result in contradictory effects on crop evapotranspiration (ETc), with insufficient knowledge available on the effects on ETc at the field level [8].

Impacts of CC on agriculture can be addressed with climate models that simulate the future climate change scenarios, based on emission scenarios. These models are classified into general circulation models (GCMs) or regional climate models (RCMs), depending on the area considered and the spatial resolution [1,4,27]. Their use is associated with uncertainty since it is difficult to model the climate system due to its complexity and the lack of knowledge. This includes the uncertainties (i) in the climatic base data due to a reduced number of meteorological stations and uneven distribution over the globe, (ii) in the knowledge of the physical and chemical processes of the climate system, (iii) resulting from the simplifications necessary to simulate a very complex system through mathematical models and (iv) from the regionalization methods, including the RCMs and their spatial resolution [28]. This is especially important in the case of precipitation which is a difficult climatic variable to model [29,30]. Another important source of uncertainty relates to the use of the Representative Concentration Pathway (RCP) scenarios, given that a high level of uncertainty exists relative to the evolution of future anthropogenic greenhouse gas (GHG) emissions, in the conversion of these emissions into future concentrations of GHG in the atmosphere and in the corresponding radiative forcing [1,4,28,29]. The Intergovernmental Panel on Climate Change (IPCC) [1] proposes Representative Concentration

Pathway (RCP) scenarios characterized by an increase in radiative forcing expressed in Wm^{-2}. RCP 2.6 is a rigorous mitigation scenario, RCP 4.5 and RCP 6.0 are intermediate scenarios and RCP 8.5 is a scenario with a very high GHG concentration [1]. The RCP scenarios usually used in CC impacts studies are RCP 4.5 and RCP 8.5.

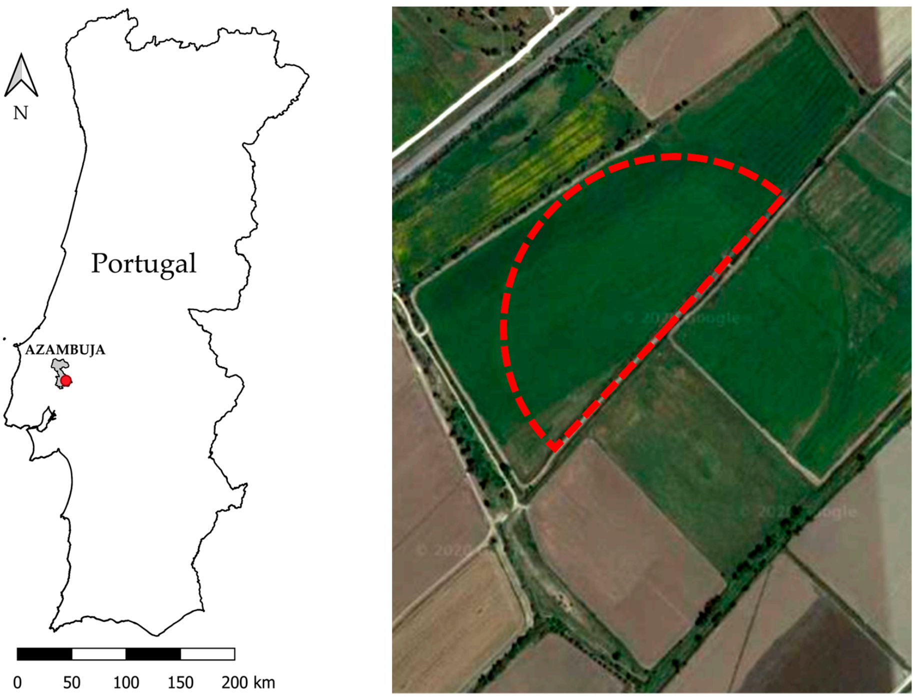
To overcome the main negative CC impacts, it is necessary to identify and evaluate adaptation measures, namely the selection of varieties and cultivars that are better adapted for the future CCS [31–34]. In order to increase water use efficiency and water productivity, under the warmer and dryer CCS, some alternative management practices can be adopted such as deficit irrigation strategies [35], the use of rescue or complement irrigation in situations of limited water availability, or the increase in the water retention capacity in the soil [31].

This study aims to evaluate the impacts of climate change on the forage irrigation requirements and to define and assess different adaptation measures concerning irrigation water management. Three adaptation measures were defined for different agronomic scenarios: (i) maximization of crop production (suitable water availability); (ii) reduction in water consumption (water shortage); (iii) rainfed crop production (lack of water for irrigation). A second objective focused on evaluating the impacts on crop water deficit caused by increased water scarcity due to CC affecting forages produced under rainfed conditions.

2. Materials and Methods

2.1. The Study Area

The present study was performed on a stud farm of *Lusitano* horses located in Azambuja, about 50 km from Lisbon, in the Ribatejo region, Central Portugal (Figure 1a), during the crop season of 2018/2019. Although the area of the stud farm is over 100 ha, the study was carried out on a 17-ha plot, where only 8 ha are dedicated to the production of irrigated forage, identified in Figure 1b, and where a center pivot is installed. The fields in this region are commonly used for rice production due to their characteristics (poor drainage conditions due to a shallow water table).



(**a**) (**b**)

Figure 1. (**a**) Map of Portugal showing the Azambuja region; (**b**) location of the experimental field highlighted in red (from Google Maps).

2.1.1. Forage

In the experimental plot, irrigated forages for horses are normally produced using a mixture of 2/3 Italian ryegrass (*Lolium multiflorum* Lam.)) and 1/3 Persian clover (*Trifolium resupinatum* L.). The first one, *Lolium multiflorum* Lam., is a grass commonly preferred by horses [36], hence the proportion of this species in the seed mixture was higher. In the 2018/2019 season, two cuts were made for haylage production and a third one for hay production. The sowing was held on 10 October 2018. The dates when the three cuts were made were 23 March, 12 May and the last one was 13 June 2019. The cutting height was 7 cm and the haylage bales were wrapped in plastic film. After the first and second cuts, nitrogen fertilization was carried out. The productivities obtained for the three cuts were 2.8, 3.4 and 2.1 tons DM·ha^{-1}year^{-1}, respectively. Therefore the total yield obtained throughout the crop-growing season was 8.3 tons DM·ha^{-1}year^{-1}.

In the 2018/19 campaign, the farmer changed the production system, going from just one cut of hay per year, to several cuts of haylage, with the latter cut for hay. This change in the production system was due to the need to increase the production of forages in the irrigated area. This would compensate for losses in the rainfed forage and pasture fields, given the decrease in the overall production of the farm as a consequence of three years of drought.

In a complementary study carried out during the experimental period [37], chemical analyses were performed to estimate the nutritive value of the preserved forage obtained for each cut. The analysis included the determination of dry matter (DM), crude protein (CP), plant structural components (Neutral Detergent Fiber—NDF, Acid Detergent Fiber—ADF and Acid Detergent Lignin—ADL) and ashes. The results obtained for haylage (first and second cuts) and hay (last cut) were, respectively, (i) 61.3%, 68.4% and 88.1% for DM content and (ii) 9.5%, 9.2% and 11.4% for CP content on the basis of DM. The quality of the forage (either haylage or hay) can be considered as medium/good according to the literature [36,38].

2.1.2. Soil Data

The soil of the experimental plot belongs to the solonchaks group according to the World Reference Base (WRB) classification system [39]. These types of soils are mineral soils whose formation was conditioned by an arid climate [39,40]. Solonchaks soils are characterized as having a moderate concentration of soluble salts, with an electric conductivity of the saturation extract between 8 and 16 dS/m [41].

The main soil hydraulic properties such as bulk density and soil water content at field capacity and at the wilting point were obtained from field samples, considering a soil depth of 20 cm, which correspond to root depth. The wilting point was determined by taking samples when the pasture was dry. Field capacity was determined by collecting samples 48 h after soil saturation, with the soil surface covered with plastic to prevent soil evaporation. The soil bulk density was determined by collecting undisturbed samples using a cylinder of a known volume [42].

To evaluate the soil water content changes during the irrigation season, the gravimetric method [43] was used. Soil samples were collected with an interval of 15 days, and with a half-cane probe up to a 20-cm depth. Soil samples were collected in four random points on each collection date. The measured soil water content data were used to calibrate the ISAREG model [24] to the prevailing conditions of the studied plot.

2.1.3. Climate Data

The climate of this region according to the Köppen–Geiger [44] classification system is a temperate climate with hot dry summers and rainy winters (Csa). At the nearest weather station (Santarém, 39°15′ N; 08°41′ W; 54 m a.s.l.), belonging to *Portuguese Institute for Sea and Atmosphere* (IPMA), the registered data relative to climate normals for the 1971–2000 period have shown monthly average air temperatures with a minimum of 9.6 °C in January and a maximum of 22.7 °C in August. The average annual rainfall for this period was 696.5 mm (Figure 2).

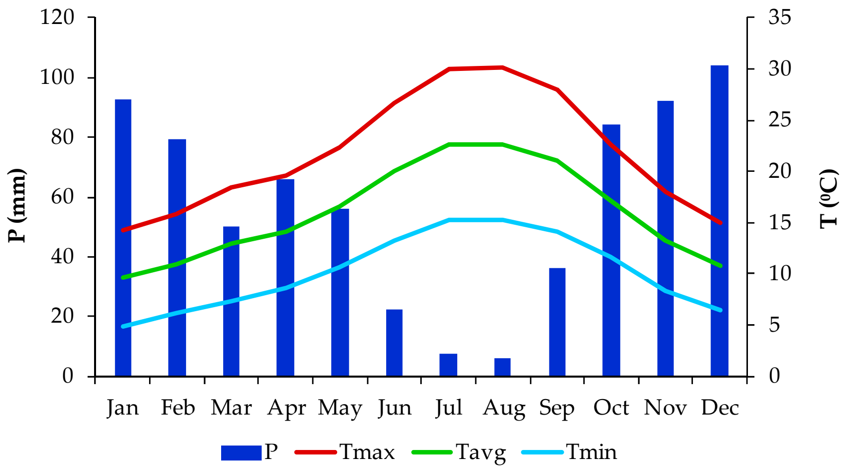


Figure 2. Annual distribution of precipitation, maximum, average and minimum air temperatures in the Santarém weather station for the 1971–2000 climate normals.

To assess the impacts of climate change on the forage crop, two climate change scenarios were considered, relative to the representative concentration pathways, RCP 4.5 and RCP 8.5 [1], for the period from 2071 to 2100. According to the IPCC [1], RCP 4.5 is a moderate scenario, since socio-economic evolution controls the increase in greenhouse effects emissions. RCP 8.5 is the more pessimistic scenario because it results from the continuous growth of GHG emissions during the 21st century. The 2071–2100 period was considered, because the use of a more distant CCS allows a clearer sign of the expected impacts on irrigation requirements over the coming decades, which is very relevant in the planning of water resources and irrigation water management that should be conducted in the long term.

Climate scenario data were obtained from the Climate Portal [45], for the "Médio Tejo" region, considering an "Ensemble" of models available on this portal. The details in the construction of the corrected future climate series, for the climate change scenarios RCP 4.5 and RCP 8.5, are given further in the text, in the corrected climate data series section (Section 2.2).

The climate variables considered in this study were maximum air temperature (Tmax, °C), minimum air temperature (Tmin, °C) and precipitation (mm d^{-1}). In the present study, the following climate data sets were used:

- Historical monthly data series for the reference period (1971-2000) were obtained from the nearest weather stations available: precipitation from the Barragem de Magos weather station (38°59′ N; 8°42′ W; 43 m a.s.l., the nearest weather station); maximum and minimum air temperatures from the Santarém weather station (39°15′ N; 8°42′ W; 61 m a.s.l.). The two stations belong to a network called Sistema Nacional de Informação de Recursos Hídricos (SNIRH). Because there were no available air temperature data for the entire period in the Barragem de Magos weather station, the Lisboa weather station (38°43′ N; 9°8′ W; 77 m a.s.l.) was used to complete temperature data gaps in the Santarém station data series, and a linear regression between Santarém and Lisboa data was used to fill the gaps (Tmin R^2 = 0.96; Tmax R^2 = 0.99).
- Monthly averages of the climate anomalies concerning climate change scenario data from 2071–2100, produced for an ensemble of Regional Climate Models (RCMs), for the "*Médio Tejo*" region available in the Portal do Clima [45], considering the RCP scenarios RCP 4.5 and RCP 8.5. These data sets were provided by IPMA [45] based on an ensemble of Regional Climate Model (RCM) data produced in the EURO-CORDEX project with a spatial resolution of 0.11 degree (~12 km) and with a daily temporal resolution.

- RCM baseline scenario precipitation data from 1971–2000, considered to be used in the bias correction of this variable in the CCS.

The Hargreaves–Samani (H–S) method [46] was used to determine ETo because there was no complete data series to compute the reference evapotranspiration by the FAO Penman–Monteith (FAO–PM) method [47]. Therefore, the H–S method was used as it only requires Tmin and Tmax data to compute ETo. Teixeira et al. [48] have previously assessed the H–S method's accuracy for the south of Portugal and the results show a good agreement between the H–S and FAO–PM for this region.

2.2. Corrected Climate Scenarios Data Series

The climate change data series must be corrected to remove bias in the simulated data produced by the RCM [30,49–51] by disturbing the weather station data series, relative to the reference period, with the climate anomalies that were produced by the RCMs. Usually, in studies related to water resources, the Delta Change method is used, as defined by Graham et al. [30], Lenderink et al. [49] and Räty et al. [51].

In this study, two CCS were considered: RCP4.5 and RCP 8.5. Historical monthly climatic data, relative to the climate normals of 1971–2000, recorded at the Santarém and Barragem de Magos weather stations, were used to produce the future climate change series. To construct the disturbed climate series for the 2071–2100 period, for each of the scenarios under study (RCP 4.5 and RCP 8.5), the climate anomalies data regarding to "Médio Tejo" region were collected from Climate Portal [45]. The collected data were the anomalies related to the monthly average precipitation, maximum and minimum temperature as well as the simulated monthly average precipitation for the reference 1971–2000 period.

To obtain the corrected climate change data series, the historical series can be disturbed by the respective anomalies both for temperature and precipitation, for each of the RCP scenarios through the following equations, using the Delta Change approach already mentioned [30,49,52]:

$$T_{\text{scenario}} = T_{\text{historical}} + T_{\text{anomaly}} \tag{1}$$

where T_{scenario} is the corrected temperature regarding the climate change scenarios; $T_{\text{historical}}$ is the temperature observed in the reference period (1971–2000) for the region under study; T_{anomaly} corresponds to the difference between the temperature simulated by the RCM for the climate change scenarios and the temperature simulated by the RCM for the reference period (1971–2000).

For precipitation, the corrected series is obtained as follows [30,49,52]:

$$P_{\text{scenario}} = P_{\text{historical}} \times \frac{P_{\text{RCMscenario}}}{P_{\text{RCMreference}}} \tag{2}$$

where P_{scenario} is the corrected precipitation regarding the climate change scenarios; $P_{\text{historical}}$ is the precipitation observed in the reference period (1971–2000) for the region under study; $P_{\text{RCMscenario}}$ is the average monthly precipitation simulated by the RCM for the climate change scenarios considered; $P_{\text{RCMreference}}$ is the average monthly precipitation simulated by the RCMs for the reference period (1971–2000).

2.3. Adaptation Measures and Agronomic Scenarios

To evaluate the impacts of CC on the irrigated forage, three adaptation measures were proposed and evaluated, corresponding to different agronomic scenarios, depending on the production objectives and water availability for irrigation.

The first adaptation measure (AM1) aims at maximizing crop production, supposing a context in which the availability of water for irrigation is not limiting. In this scenario, the crop is irrigated using the full length of the current growing season (October–May), in which the shortening of the crop cycle caused by the increase in temperature allows the number of cuts made during the crop season to increase.

The second adaptation measure (AM2) aims at saving water, in a situation where there is a significant reduction in water availability, assuming a decrease in production. In this option, irrigation is maintained but only one cut is made, reducing the crop growing season. Under the CC scenarios, the crop cycle will be shortened, reducing the exposure to the driest and warmest period of the growing season, which will determine considerable savings in irrigation water consumption.

The third option (AM3) is an extreme scenario in which there is no available water for irrigation and where forage will have to be produced under rainfed conditions. In this case, it is important to evaluate the crop water deficit that occurred in the CCS, with the main objective of evaluating the sustainability of this crop under rainfed conditions.

2.4. Crop Cycle Adjustment for the Future Climate Scenarios

The future CCSs will lead to an increase in mean air temperature, which will shorten the length of the crop cycle, as there is a faster accumulation of growing degree-days.

The thermal time, the number of growing degree-days (GDDs) that a crop needs to accumulate to complete its cycle, allowed (i) to predict the CC effects on the forage crop phenology, (ii) to assess the number of possible cuts for each CC scenario and (iii) to adjust the crop coefficient curve, allowing the evaluation of CC impacts on the forage water consumption. Given the faster accumulation of GDDs, the crop cycle was adjusted according to the thermal time, for both RCP scenarios.

The crop stage lengths were adjusted according to the thermal time required to accomplish each of them. The GDDs were calculated for different periods: (i) the reference period (1971–2000), (ii) the 2018–2019 experimental period, (iii) scenario RCP 4.5 (2071–2100) and (iv) scenario RCP 8.5 (2071–2100). The first period (1971–2000) was used to define the GDDs required to make just one single cut in mid-May, corresponding to the traditional production method. The second period (2018–2019) was used to define the thermal time required for each additional cut, using the new production strategy of performing several cuts. The last two periods correspond to the scenarios of climate change. Based on these values, it was possible to adjust the crop growth stages for the CCS and to predict the maximum number of possible cuts. The length of the growing season was kept, from October to May, to compare the increase in the crop irrigation requirements for the RCP 4.5 and RCP 8.5 scenarios, for a similar period.

The GDDs were determined with the following equation [53]:

$$\mathrm{GDD} = \sum \left(\frac{\mathrm{T_{max}} + \mathrm{T_{min}}}{2}\right) - \mathrm{T_{base}} \tag{3}$$

where $\mathrm{T_{max}}$ and $\mathrm{T_{min}}$ are maximum and minimum daily temperatures, respectively, and T_{base} is the base temperature, which is a constant value for each crop. According to Hutchinson et al. [54] and Moreira [38], the base temperature of *Lolium multiflorum* Lam. (Italian ryegrass) is around 5 °C, a value that was assumed as the crop vegetative zero. For *Trifolium resupinatum* L. (Persian clover), the other plant present in the consociation, the crop vegetative zero varies between 5.2 and 5.7 °C [55]. Therefore, in the present study, a base temperature value of 5 °C was assumed, since the studied forage was composed by 2/3 of ryegrass.

2.5. Climate Change Impacts Modeling and Adaptation Measures Evaluation

The CC impacts on irrigation requirements and crop water deficit values, respectively, for the irrigated and rainfed forage, were estimated using the ISAREG model [24]. Firstly, the ISAREG model was calibrated during the 2018/19 period, for the experimental field condition. Based on the crop parameters and on the contribution of the water table, adjusted during this calibration, the impacts of future CCSs were simulated and the different adaptation measures were evaluated considering the different climate scenarios (Figure 3).

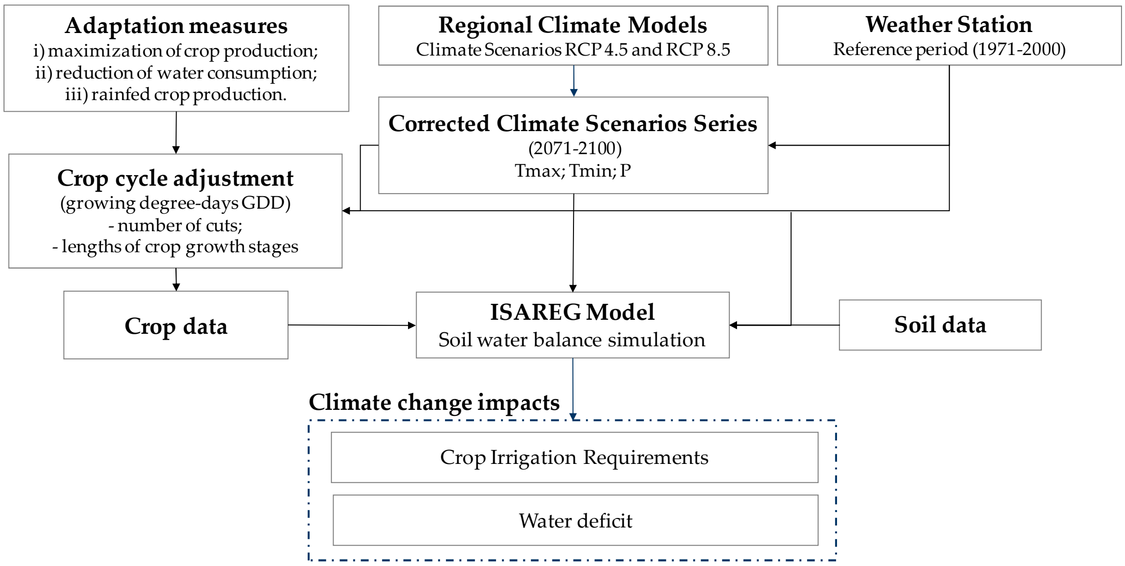


Figure 3. Flowchart of the climate change impact evaluation.

Irrigation Requirements Modeling

To perform the simulation of the impacts of CCS on the forage water requirements, the soil water balance model ISAREG was used. This model has been validated for several regions and crops, including winter cereals [25] and grassland [26], and proved to accurately estimate crop irrigation requirements. The ISAREG model was also used to assess the impacts of climate change on several irrigated crops in the studies of Valverde et al. [3,21] and Popova [20], which validate and support the confidence level for the results obtained by this model.

The ISAREG model [24] uses meteorological, crop, soil, irrigation schedule restrictions and water management data as inputs to simulate the soil water balance. This model allows to schedule irrigation, to determine the crop water requirements, to define the design parameters of irrigation systems (e.g., design flow rate) and to evaluate a given irrigation calendar. The ISAREG model performs the calculation of the crop irrigation requirements, using daily or monthly meteorological data, by simulating the soil water balance according to the following equation:

$$\Delta S = P - ETc + Ir - Ro + CR - DP \tag{4}$$

where ΔS is the variation of the soil water storage (mm), P is precipitation (mm), ETc is the crop evapotranspiration (mm), Ir is irrigation depth (mm), Ro is surface runoff (mm), CR is the capillary rise (mm) and DP is deep percolation (mm).

The crop water deficit (WD), expressed in percentage, is calculated as the difference between the sum, throughout the growing season, of the crop evapotranspiration (ETc) under full irrigation and the sum of the crop evapotranspiration, adjusted (ETc_{adj}) to the soil water limiting conditions and divided by the sum of ETc [8,47]:

$$WD = 100 \times \frac{\sum ETc - \sum ETc_{adj}}{\sum ETc} \tag{5}$$

ETc_{adj} is obtained by multiplying the crop coefficient (Kc) by the water stress coefficient (Ks) when the soil water depletion exceeds the readily available water, as described by Allen et al. [47].

In this study, the main objective of using the ISAREG model was to estimate the irrigation requirements of irrigated forage and to determine the water deficit that would occur when the crop is produced under rainfed conditions. Usually, the approach used in the modeling of climate change impacts on crop water requirements is based on the use of crop values obtained from the literature, with similar conditions to where the impacts are to be assessed and is a well-proven model [3,16,21–23].

To perform the soil water balance simulation, crop data from [47] were used, which followed the model calibration, to confirm the adequacy of the data used to estimate crop water requirements.

The ISAREG model was calibrated for local conditions before performing the simulations for the different climate scenarios and adaptation measures. The calibration was performed by comparing the soil water content (SWC) values (measured by the gravimetric method), with the values simulated by the model, taking into account the 2018/19 climate data, the information on irrigation depths (provided by the farmer) and accounting for the capillary rise.

The experimental field is equipped with a center pivot. During the experimental period (2018/2019), irrigation started after the first cut (March 28) and was finished on June 2, ten days before the last cut. Fixed water depths of 3.6 mm were applied at variable time intervals and, during the most demanding period, from the second half of May until the end of the irrigation season, irrigation was applied every two days. The seasonal irrigation depth applied throughout the crop cycle was approximately 83 mm (according to the information provided by the farmer). The crop irrigation requirements (CIRs) were computed for the reference period and for the RCP 4.5 and RCP 8.5 scenarios, selecting the global irrigation requirements option of the ISAREG model. This option, calculates the theoretical net crop irrigation requirements, simulating the application of small irrigation depths of 1 mm to compensate crop evapotranspiration as soon as the readily available water (RAW) threshold is reached, avoiding the error in the calculation of CIR due to a final value of SWC being above the RAW threshold.

Table 1 shows the values of the crop parameters, including the crop coefficients (Kc), used in the calculation of the crop irrigation requirements for the CCS. Crop coefficient values were derived from Allen et al. [47]. Both in the reference period and for the future CCS, the initial Kc was 0.3 as ryegrass presents slow initial growth. The value of Kc_{end} = 1 corresponds to the forage cut at the beginning of senescence stage when only one cut was made, which corresponds to the traditional production system (AM2). The second and third cuts (AM1) were made at the end of the mid-season stage, with cut heights of 7 cm. Therefore, the forage Kc after the cut is 0.6, which corresponds to the crop that remains in the field, with a height of 7 cm at full cover in the initial stage of the second and third cuts.

Table 1. Crop parameters used to compute crop water requirements.

	***Lolium multiflorum* Lam. × *Trifolium resupinatum* L.**		
	Reference Period	**RCP 4.5**	**RCP 8.5**
Sowing day	15	15	15
Sowing month	10	10	10
L_{ini} (days)	30 (1C)	27 (1C),16 (2C)	23 (1C),14 (2C),12 (3C)
L_{dev} (days)	135 (1C)	117 (1C),23 (2C)	103 (1C),22 (2C),18 (3C)
L_{mid} (days)	40 (1C)	35 (1C)	30 (1C)
L_{late} (days)	5 (1C)	4 (1C)	4 (1C)
$Kc_{\_ini}$	0.3	0.3	0.3
$Kc_{\_mid}$	1.05	1.05	1.05
$Kc_{\_end}$	1	1	1
Depletion fraction: p	0.6	0.6	0.6
Max. rooting depth (m)	0.25	0.25	0.25

Representative Concentration Pathway (RCP); Lengths of crop growth stages: L_{ini}—initial stage; L_{dev}—crop development stage; L_{mid}—mid-season stage; L_{late}—late season stage. Crop coefficient: $Kc_{\_ini}$—initial stage; $Kc_{\_mid}$—mid-season stage; $Kc_{\_end}$—at the end of the late season stage. The first, second and third cut are represented by 1C, 2C, and 3C, respectively.

3. Results and Discussion

3.1. Soil Parameters and Model Calibration

3.1.1. Soil Parameters

Field observations were performed in order to obtain the soil parameters that were used as inputs in the ISAREG model. The solonchaks soil in the studied plot had a heavy clay texture. The observed values for the soil water content were $\theta_{FC} = 0.44$ m^3 m^{-3} at field capacity and $\theta_{WP} = 0.27$ m^3 m^{-3} at permanent wilting point, and the bulk density was 1.29 g cm^{-3}.

3.1.2. ISAREG Model Calibration for the Local Conditions

The ISAREG model was calibrated for the 2018/19 crop growing season, comparing the soil water content values measured in the field with the simulated values produced by the model, confirming its adequacy to estimate forage irrigation requirements. In the present study, one year of measured soil water content data were considered adequate to perform the model calibration. Soil water balance is a simplified methodology to estimate crop water consumption with some degree of uncertainty, which is not possible to eliminate totally. Additionally, in studies concerning the impacts of climate change on crop water requirements, there is uncertainty regarding plants' responses to climate change, namely concerning the effect of an higher concentration of CO_2 on crop evapotranspiration and, therefore, the use of a longer experimental data set may not significantly increase the simulation accuracy for the CCS.

The capillary rise contribution was estimated using the ISAREG model through an iterative process. A value of 2 mm/d was obtained for the potential capillary rise based on the methodology presented in Doorenbos and Pruitt [56]. Measured and simulated values of soil water content are shown in Figure 4.

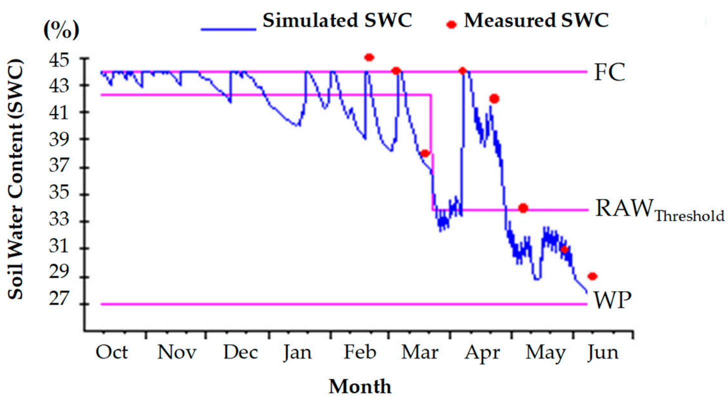
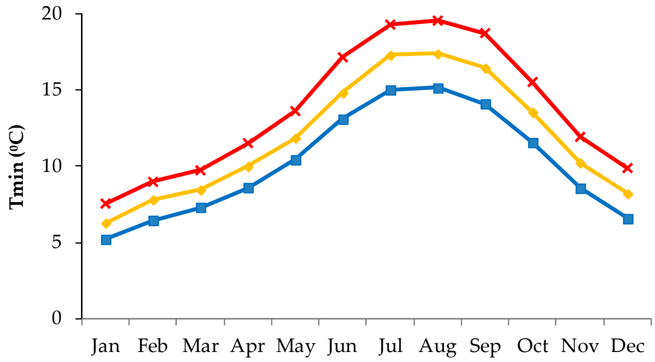


Figure 4. Measured and simulated values of soil water content considering a root depth of 20 cm. The blue line is the soil moisture content simulated by the ISAREG model and the red points correspond to the soil moisture content values measured in the field using the gravimetric method ($RAW_{Threshold}$—threshold for the readily available water, field capacity—FC, permanent wilting point—WP).

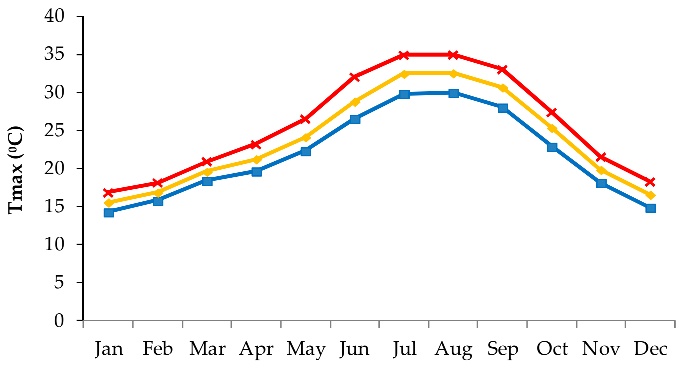
The ISAREG model does not consider the occurrence of capillary rise when the soil water content is above the readily available water (RAW) threshold. As the studied field presents a shallow water table at approximately 25 cm in the winter, with an important contribution of capillary rise to the crop water consumption, it was necessary to consider this component. Therefore, to consider the capillary rise contribution, in the initial part of the crop cycle (winter), it was necessary to increase artificially the RAW threshold (with a depletion fraction, p, of 0.1), because the ISAREG model capillary rise routine requires the existence of water stress to estimate and introduce the capillary rise in the soil water balance. The comparison between simulated and measured soil water content values showed that the ISAREG model is capable of accurately simulating the forage irrigation requirements, for the conditions of the studied plot (Figure 4).

3.2. Corrected Climate Scenarios Data Series

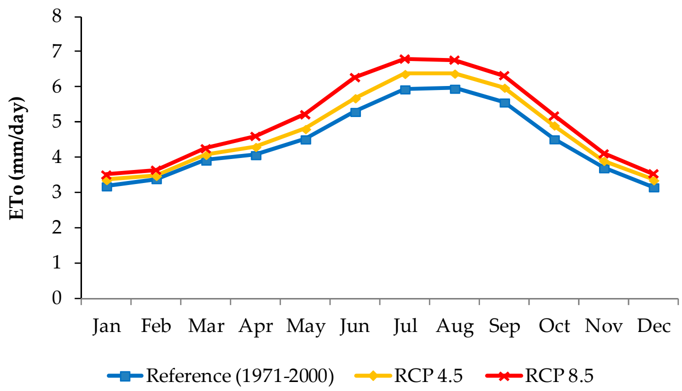
The corrected climate change series for the maximum temperature, minimum temperature, reference evapotranspiration and precipitation are presented in Figure 5. This figure allows a comparison to be made between the considered scenarios (RCP 4.5 and RCP 8.5) with the reference period (1971–2000).



(**a**)

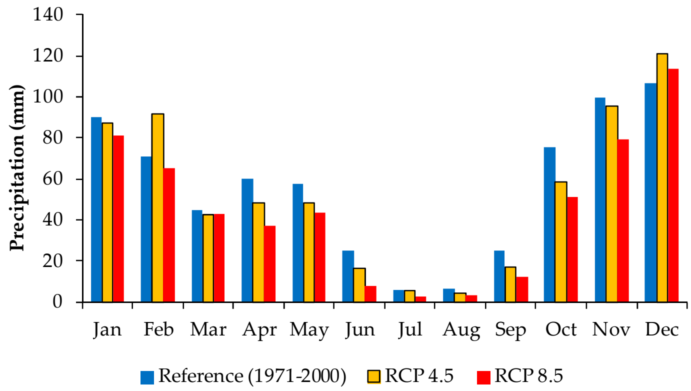


(**b**)



(**c**)

Figure 5. *Cont.*



(**d**)

Figure 5. Monthly average values of (**a**) minimum temperature, (**b**) maximum temperature, (**c**) reference evapotranspiration and (**d**) precipitation for the reference period (1971–2000) and for the climate change scenarios Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 (2071–2100).

Considering monthly average temperatures, this study indicated an average increase of 1.8 °C for RCP 4.5 and 3.7 °C for RCP 8.5 (Figure 5a,b and Table 2), which is in line with the values reported by Pires et al. [5] and by the IPCC [1] for the Mediterranean region. According to Pires et al. [5], in Portugal, the average temperature is expected to be higher for both future CCSs—approximately +2 °C for scenario RCP 4.5 and +4 °C for RCP 8.5.

Table 2. Average temperature anomalies for the RCP 4.5 and RCP 8.5 scenarios (2017–2100) in comparison to the reference climate normal (1971–2000).

	Tavg Reference (°C) (1971–2000)	Anomaly RCP 4.5 (°C) (Tavg $_{\text{RCP 4.5}}$–Tavg $_{\text{reference}}$)	Anomaly RCP 8.5 (°C) (Tavg $_{\text{RCP 8.5}}$–Tavg $_{\text{reference}}$)
January	9.8	1.2	2.4
February	11.1	1.2	2.4
March	12.9	1.2	2.5
April	14.2	1.5	3.2
May	16.4	1.6	3.7
June	19.9	2.0	4.8
July	22.5	2.4	4.7
August	22.6	2.4	4.7
September	21.1	2.5	4.8
October	17.2	2.2	4.2
November	13.4	1.7	3.4
December	10.8	1.7	3.3
Mean	16	1.8	3.7

Regarding the reference evapotranspiration (Figure 5c), the greatest increase due to the CCS occurred during spring and summer. In the autumn and winter periods, ETo values were very similar between the different climate scenarios. In addition, precipitation in the CCS will tend to be more concentrated in the winter, while reference evapotranspiration will tend to suffer a main increase in spring and summer (Figure 5d). The opposite trends of these two variables impaired the growth conditions of rainfed forage and increased its dependency on irrigation to ensure crop production.

For both RCP scenarios, between April and June, the precipitation will be also considerably lower than in the reference period (Figure 5d). According to the same figure, in December, an increase in precipitation for the future climate scenarios is anticipated. It should be noted that in the RCP scenario 4.5, the second month of the year presents a peak (around 90 mm) when compared to the reference period (approximately 65 mm). As expected, in the remaining months of the year, precipitation for the future climate scenarios will be lower than in the reference period.

The average annual precipitation anomalies for the period 2071–2100 (in comparison to the reference period, 1971–2000) presents, for the RCP 4.5 scenario, an average reduction of 3.8%, and as expected, the percentage of reduction for the most severe scenario (RCP 8.5) is higher, at around 15%. The anomaly value obtained for the RCP scenario 4.5 is, for this region, slightly lower than the value reported by Pires et al. [5]—on average 5%. The calculated value for the RCP 8.5 scenario is in the range of 10%–30% proposed in the literature [1,4,5].

The analysis of the precipitation that occurred during the studied season (2018/2019) was also performed. Figure 6 shows that the precipitation that occurred during this period was very scarce during the winter (the 2018/2019 winter being classified by the IPMA as extremely dry) [57]. This event may be one of the factors that contributed to the increase in crop productivity (observed in the field) since plants were not exposed to flooding and developed in better drainage conditions.

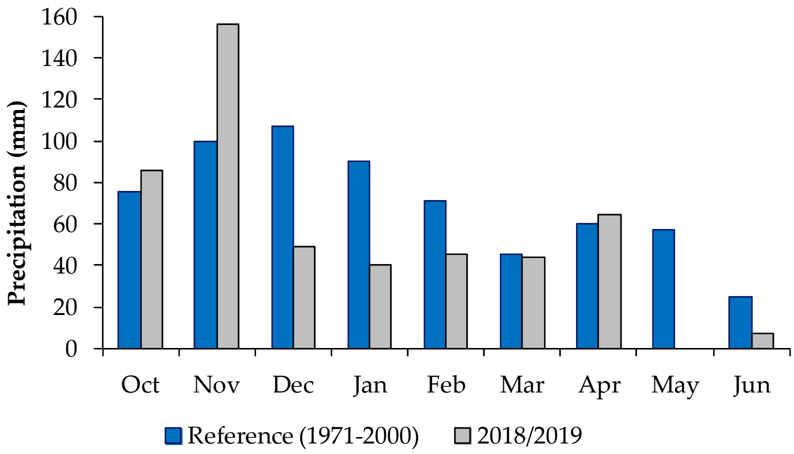


Figure 6. Precipitation distribution over the growing season of 2018/2019.

3.3. Number of Cuts and Length of Crop Growth Stages

The thermal integral (growing degree-days, GDDs) was calculated for the four periods/scenarios under analysis: reference period (1971–2000), experimental period (2018/19), RCP 4.5 and RCP 8.5 (2071–2100). The thermal time accumulated during the growing season (October to May), for the different climate scenarios is presented in Figure 7. It is possible to observe that the results obtained for the 2018/2019 period are very similar to those of the reference period (1971–2000) and that, at certain periods, they are even slightly lower when considering temperature accumulation. Therefore, it can be concluded that the increase in the number of forage cuts (three) made by the farmer in the 2018/19 period (in previous years just one cut was made), was not a consequence of an increase in temperature since the average air temperature had similar behavior to that of the climate normal of 1971–2000. Instead, it was due to a change in the farmer's behavior, corresponding to an adaptation to drought periods, which is becoming more frequent in recent years.

The GDDs computed for each climate scenario are presented in Table 3. It takes approximately 210 days to make a single cut in the reference period, which corresponds, on average, to an accumulation of 1623 GDDs (Table 3). In the case of the 2018/19 period, the accumulated value was 1118 GDDs until the first cut, corresponding to an earlier crop stage at the time of the cut. The values of the thermal time reached for the last two cuts were 500 and 445 GDDs, respectively. Therefore, these values were considered as the range of values required to make an additional cut. The 2018–2019 experimental period corresponded to the introduction, by the farmer, of multiple cuts in the production system. It is, in fact, a reduced time period to define the thermal time of the additional cuts. However, the GDDs obtained for the second and third cuts were very similar (in periods with very different temperature, solar radiation and humidity conditions), which means that it can be assumed that the obtained values can give an acceptable estimate of the GDDs required for the additional cuts. Thus, it can be concluded that, for scenario RCP 4.5, it will be possible to make two cuts in 222 days (1601 + 477 GDDs) and that, in the context of a greater increase, in the scenario RCP 8.5 it may be possible to make three cuts in 226 days (1603 + 448 + 453 GDDs). In the RCP 8.5 scenario, slightly lower values were considered for the second and third cuts than for RCP 4.5 to allow the crop cycle to finish by the end of May. The results obtained show that for the future CCS, the air temperatures will be higher and will lead to faster crop development [12], allowing more cuts to be made in the same period. The results obtained in Soares [37] show that the execution of additional cuts did not seem to compromise the overall forage quality, suggesting that this new production strategy, with multiple cuts, could be a viable adaptation measure to CC both in what concerns forage productivity and quality.

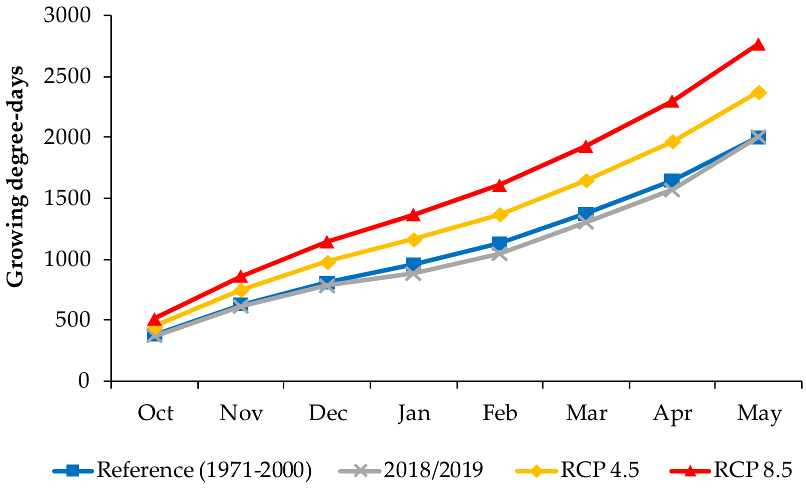


Figure 7. Growing degree-days accumulated for the reference period (1971–2000) for the 2018/2019 period and the RCP 4.5 and 8.5 scenarios (2071–2100).

Table 3. Growing degree-days, number of cuts and harvesting dates for the climate scenarios.

		Fist Cut		Second Cut		Third Cut	
	Sowing	Harvesting	GDD	Harvesting	GDD	Harvesting	GDD
Reference (1971–2000)	15/October	15/May	1623	-	-	-	-
2018–2019	15/October	23/March *	1118	12/May	500	13/June	445
RCP 4.5 (2071–2100)	15/October	17/April	1601	26/May	477	-	-
RCP 8.5 (2071–2100)	15/October	25/March	1603	01/May	448	31/May	453

* in 2018–2109 forage first cut was performed in an early crop stage.

Some examples of the crop coefficient (Kc) curves built for the different climate scenarios, with the lengths of crop growth stages adjusted according to the accumulated GDDs, are shown in Figure 8. For the reference period (1971–2000) only one cut was considered, corresponding to the traditional production system of hay (Figure 8a). Considering the first adaptation measure (maximization of crop production), in the RCP 4.5 scenario, two cuts were made (Figure 8b), and for the RCP 8.5 scenario it will be possible to perform three cuts due to a faster accumulation of the thermal time (Figure 8c). These Kc curves were used to simulate the soil water balance and correspond to the lengths of the crop growth stages presented in Table 1.

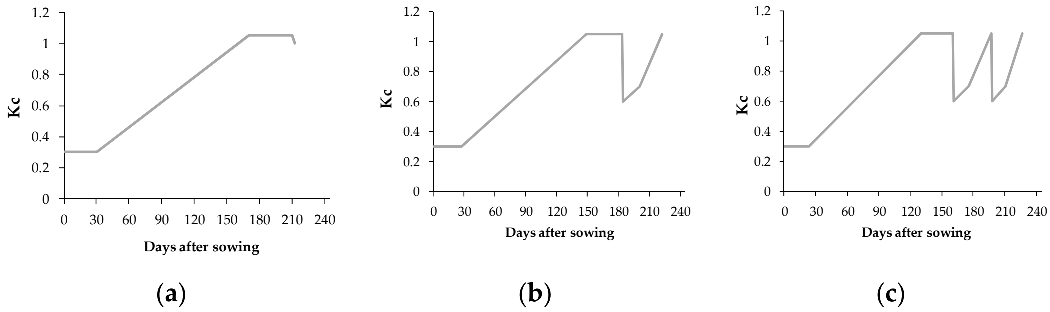


Figure 8. Crop coefficient curves, with the length of the crop growth stages adjusted to the function of growing degree-days (GDDs), (**a**) for the reference period (1971–2000), making just one cut (AM2), (**b**) for the RCP 4.5 scenario with two cuts (AM1) and (**c**) for the RCP 8.5 scenario with three cuts (AM1).

3.4. Crop Irrigation Requirements

The net irrigation requirements simulated for the different CCSs and adaptation measures are presented in Figure 9, where it is possible to observe a high interannual variability and the high influence of the adaptation measures in future water consumption for irrigation. According to the results obtained for the GDDs, whenever water is available for irrigation, two cuts can be carried out in scenario RCP 4.5 and three in scenario RCP 8.5 (maintaining the length of the present growing season), which corresponds to the adaptation measure AM1. The results for the CCS show that the increase in the number of cuts for AM1 will increase the crop irrigation requirements (CIRs) (Figure 9) when compared with the reference period—between 38.4% for RCP4.5 and 67.1% for RCP8.5 (Figure 9). This increase in CIRs corresponds to a more unfavorable situation since it was considered a more distant scenario (2071–2100), maintaining the present length of the growing period. On the other hand, in conditions of water scarcity (AM2), farmers will be pressed to reduce the consumption of water for irrigation, making only a single cut in both RCP scenarios, which results in a reduction in the CIR in relation to the reference period—31.1% and 64.0%—for the RCP 4.5 and RCP 8.5 scenarios, respectively (Figure 9). This reduction in the CIR is due to the increase in the mean air temperatures that will shorten the crop growth cycle, reducing the exposure of plants to the most critical period that occurs in the late spring. The shortening of the crop cycle implies a reduction in crop yield, since the period during which the plant produces biomass is reduced [58]. Therefore, it can be anticipated that the impacts of climate change will either result in an increase in water demand for irrigation or a reduction in crop yield due to the increased water scarcity. This will lead to forage production becoming increasingly more dependent on irrigation, resulting in aggravated production costs and, consequently, reduced farmer income, as presented by Fragoso and Noéme [17].

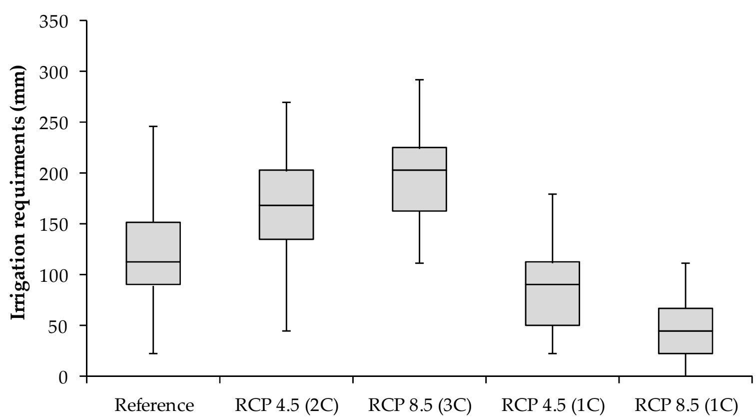


Figure 9. Box plots of the forage irrigation requirements for the reference, RCP 4.5 and RCP 8.5 scenarios, considering two (2C) and three (3C) cuts (AM1), and only one cut (1C) (AM2).

3.5. Rainfed Water Deficit

When there is no water available for irrigation—for example, in prolonged periods of drought—forage will have to be produced under rainfed conditions (AM3), making only one cut with the plants growing under water deficit conditions. The ISAREG model allowed the simulation of the water deficit for the different climate scenarios. The average crop water deficit values, along the growing cycle, are shown in Figure 10.

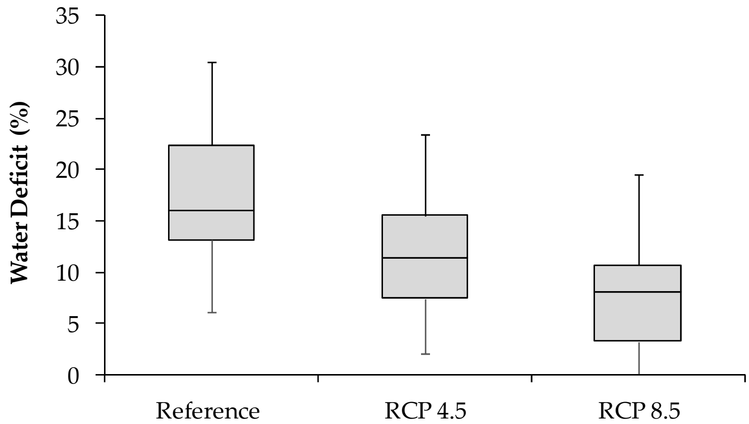


Figure 10. Box plots of the rainfed forage (AM3) water deficit for the reference, RCP 4.5 and RCP 8.5 scenarios.

In the reference period, the water deficit values are, on average, 17.1%. In the CCS, water deficit values are lower, presenting average values of 11.7% and 7.3% for RCP 4.5 and RCP 8.5, respectively. The water deficit values of the rainfed forage are smaller for the CCS than in the reference period. This occurs due to the increase in temperature (observed in each scenario), which results in the shortening of the crop cycle, causing an shorter exposure to the most critical period during the late spring, characterized by high ETo values and a lack of precipitation. Therefore, the water deficit will be smaller in the more extreme CCS (RCP 8.5). It should be noted that this reduction in the water deficit values in the CCS implies a reduction in crop production due to the shortening of the growing season.

It is important to recognize that in the experimental field capillary rise has an important contribution to the soil water balance, due to the shallow water table and, for that reason, the water deficit values presented are relatively low, indicating the suitability of this kind of field for forage production under water scarcity conditions.

4. Conclusions

The expected impacts of climate change on forage irrigation water consumption and on water deficit of rainfed forage were evaluated for a *Lusitano* horse stud farm located in a central region of Portugal under Mediterranean conditions.

The future climate change scenario data allow projections, for this region, which show an increase in air temperature ranging between 1.8 and 3.7 °C, for the scenarios RCP 4.5 and 8.5, respectively. For precipitation, an annual reduction between 3.8% and 15% is anticipated, this reduction being more marked during the spring, with a strong impact on the productivity of the rainfed autumn–winter forage.

Regarding the impacts on the crop cycle, if the growing season is kept unchanged (October–May) for both RCP scenarios, two forage cuts can be made in the RCP 4.5 scenario and three cuts in the RCP 8.5. This is supported by the increase in air temperature, which shortens the length of the crop cycle, allowing a higher number of cuts.

The evaluation of the proposed adaptation measures allowed to conclude that, for an agronomic scenario of ample water availability for irrigation, the producers can adopt a strategy of maximization of crop production making several cuts. However, the increase in the number of cuts and, consequently, in global forage production, will increase the crop irrigation requirements between 38.4% and 67.1%.

Considering an agronomic scenario with reduced water availability for irrigation, the producers can adopt the second adaptation measure aiming at reducing water consumption. In these conditions, only one cut is made, assuming a reduction in crop productivity, but also reducing the irrigation requirements for the scenarios RCP 4.5 and RCP 8.5 (2071–2100), respectively, between 31.1% and 64.0%, in comparison to the reference period (1971–2000).

In a more severe scenario, where there is a lack of water for irrigation, a third adaptation measure can be adopted, consisting of producing forage under rainfed conditions. The water deficit values, on average, will be reduced from 17.1% in the reference period to 11.7% and 7.3% for RCP 4.5 and RCP 8.5, respectively, because the period with higher temperatures and a lower relative humidity is avoided, due to the shortening of the growing cycle.

In the studied field, the existence of a shallow water table was also verified. The important contribution of capillary rise to the satisfaction of the crop water requirements makes this type of plot traditionally used for rice production have a high aptitude for forage production, when the production under rainfed conditions may be compromised. Thus, in the context of increasing water scarcity due to CC impacts, it is possible to use uncommon production areas, such as plots normally subject to flooding (such as the present case study) for forage production, in order to ensure the necessary amounts for a proper feed management of a stud farm.

In conclusion, for the conditions under study, climate change impacts on the forage irrigation requirements are very dependent on the adaptation measures implemented by the producers, and particularly on the availability of water for irrigation.

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Conflicts of Interest: The authors declare no conflict of interest.

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